Cloud Structure and Entrainment in Marine Atmospheric Boundary Layers

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LONG-TERM GOALS

Our long-term goals are to understand the dynamics of atmospheric motions on scales of order 10 m - 10 km in sufficient detail to be able to provide a consistent subgrid scale model that will represent the influence of turbulent transport across a range of scales.

OBJECTIVES

The chief objective of the present grant is to better understand the physical processes, which control cloud and circulation structure in the atmospheric boundary layer and rate of entrainment of heat and moisture across the capping inversion. This understanding will be used to formulate a consistent, robust single-column model to represent these processes in Mesoscale models for a broad range of boundary layer conditions and forcings.

APPROACH

This research utilizes high-resolution turbulent transport codes and theoretical understanding developed under previous ONR support. Our principal approach is to employ large eddy simulations (LES) to conduct controlled numerical studies of the effects of different boundary layer forcings and conditions (initial temperature and moisture profiles, surface heat and moisture fluxes, cloud-top radiation, wind shear, etc.) on the boundary layer dynamics, cloud structures and entrainment rates that result. The simulations are motivated by and compared with field observations when available. The simulation results are used to develop and test theoretical models for the basic physical processes at work, in order that these effects can eventually be consistently incorporated into lower resolution models.

WORK COMPLETED

During the past year we have concentrated on developing and testing buoyancy flux models for partly cloudy layers (Lewellen and Lewellen, 2003, LL03 hereafter). We developed an approximate expression for buoyancy flux formulated solely in terms of the liquid potential temperature and total

water profiles and their respective flux profiles. The model predictions compare favorably with the results of an extensive set of large eddy simulations, including simulations of stratocumulus, shallow cumulus, and transitional behavior in between. This formulation was combined with previous results (Lewellen and Lewellen, 2002) on the relation between cloud-top entrainment rate and circulation structure to predict the behavior of quasi-steady cumulus-coupled boundary layers as a function of a basic set of physical input parameters. These predictions also compare quite favorably with LES results.

We have also conducted a series of simulations aimed at understanding the observations of nocturnal marine stratocumulus taken in July 2001 during DYCOMS-II (the second study of the Dynamics and Chemistry of Marine Stratocumulus) (Stevens et. al., 2003). Some of these simulations are for a model intercomparison coordinated by the GCSS (GEWEX Cloud Systems Studies) boundary layer cloud modeling working group. Results from a previous GCSS intercomparison, simulations of the diurnal cycle of marine stratocumulus, were written up and submitted for publication (Duynkerke et al. 2003).

We have participated in two additional intercomparison collaborations: submitting results (LES and 1D) of an artic stable boundary layer case for the first GABLS (GEWEX Atmospheric Boundary Layer Study) (http://www.gewex.org/gabls.htm) intercomparison; and simulations of convective boundary layers in a study of the effects of shear on entrainment organized by Dr. E. Fedorovich.

RESULTS

In a partly cloudy atmospheric boundary layer we can formally write the horizontal mean buoyancy flux as,

$$\langle w'B' \rangle = (1-R)D + RW \qquad (1)$$

where D(z) and W(z) represent the "dry" and "wet" buoyancy fluxes that would result if the layer were all clear or all cloudy, respectively, at height z, and R(z) represents the ratio of the actual liquid water flux to the liquid water flux that would arise for completely cloudy conditions. To good approximation D and W can be expressed as linear combinations of the fluxes of two conserved quantities, liquid potential temperature (θ_l) and total water (q_t). If the vertical velocity and cloud water were completely uncorrelated then (1) would hold with R(z) equal to the mean partial cloud fraction. This is generally not the case, however, particularly for shallow cumulus, where the actual R can exceed the cloud fraction by a large factor. For this reason buoyancy flux modeling in partly cloudy boundary layers has been a longstanding challenge.

Motivated by LES results and mass flux models of cumulus plumes, we have developed an approximate formulation of R that can be written in the form (LL03),

$$R \approx (q_l^{sc} - q_l^{b})/(s^{sc} - s^{b}) \qquad (2)$$

where $q_l^{sc}(z)$ is the liquid water of a parcel at height z that has near-surface values of θ_l and q_t (with the fluctuations in those values approximately accounted for), s^{sc} is the difference between the total water and saturation mixing ratios of such parcels, and q_l^{b} and s^{b} are the analogous quantities for parcels with the mean θ_l and q_t at the height z.

The only information we use to evaluate (2) are the mean θ_l and q_t profiles. This formulation has the advantage of not requiring knowledge of less accessible quantities such as the mean liquid water, cloud fraction, saturation variance, or vertical velocity skewness, as in related formulations. Comparison with a broad range of LES results has shown that the formulation does a good job representing the buoyancy flux, bridging between the limits of layers that are well characterized by joint-Gaussian pdfs (such as stratocumulus) and cumulus-coupled layers with strongly correlated clouds and updrafts and very low cloud fractions. The formulation performs particularly well for transitional layers in between uniform stratocumulus and well developed shallow cumulus. The behavior in such cases (e.g., cumulus under stratocumulus) differs from that predicted by the formulation of Bechtold and Siebesma 1998, which was empirically fit to the limits of very high or very low cloud fraction. In the present formulation there is not a one-to-one correspondence between the effective cloud fraction R and the mean cloud fraction. The underlying dynamical regime is important and is reflected in the structure of the θ_l and q_t profiles. This conclusion is supported by the LES results.

This formulation for the buoyancy flux allowed us to extend our previous work on entrainment and quasi-steady structure in cloudy boundary layers: first using it to predict entrainment rates for partly cloudy cumulus layers that are in good agreement with LES results; and second, using this result to predict the equilibrium structure in those layers. In Lewellen and Lewellen 2002 it was argued that the feedback between large-scale circulation structure and entrainment into the boundary layer from above is a critical ingredient in determining the quasi-steady properties a layer will equilibrate to, including the θ_l and q_t profile shapes. By postulating a one-parameter family of profiles for these conserved variables, it is possible to use the entrainment constraints to choose from among this family. The predictions require only a minimal set of input parameters to be given (the surface fluxes of θ_l and q_t, their mean subcloud values, their respective jumps across the top of the layer at z_i, and specified vertical profiles of any sources they may have within the layer) and the results are in good agreement with those from LES for an extensive set of cumulus-coupled cases. Figure 1 illustrates examples of the comparison. Given the limitations of the one parameter family of θ_l profiles chosen (which were simply assumed linear within the cloud layer), the predictions for all the profiles capture the basic structure of the quasi-steady LES results quite well. Much is predicted from a minimal set of physical inputs, without invoking a posteriori features of the LES results such as the buoyancy flux, cloud fraction, entrainment rate, or temperature and moisture differences between the cloud and subcloud layers.

The success of these predictions for many different cases supports the validity of the underlying physical balances assumed to produce the quasi-steady equilibrium for shallow cumulus layers. This evidence for a large-scale balance constraining the buoyancy flux may in part explain the results from LES studies (e.g., Brown 1999) showing insensitivity to resolution and subgrid model of the mean flux profiles for quasi-steady cumulus simulations even though the structure of the individual cumulus plumes shows a clear sensitivity.

Our LES studies of the first research flight of DYCOMS-II seem to support one of the most interesting findings of the observations: the maintenance of a solid stratocumulus cloud deck and a coupled well-mixed boundary layer despite cloud-top conditions that would seem to foster buoyancy reversal, cloud breakup and decoupling of the layer. This result does show some sensitivity to subgrid modeling of buoyancy reversal at cloud top. An upcoming GCSS model intercomparison of simulations based on this case should address how robust these results are.

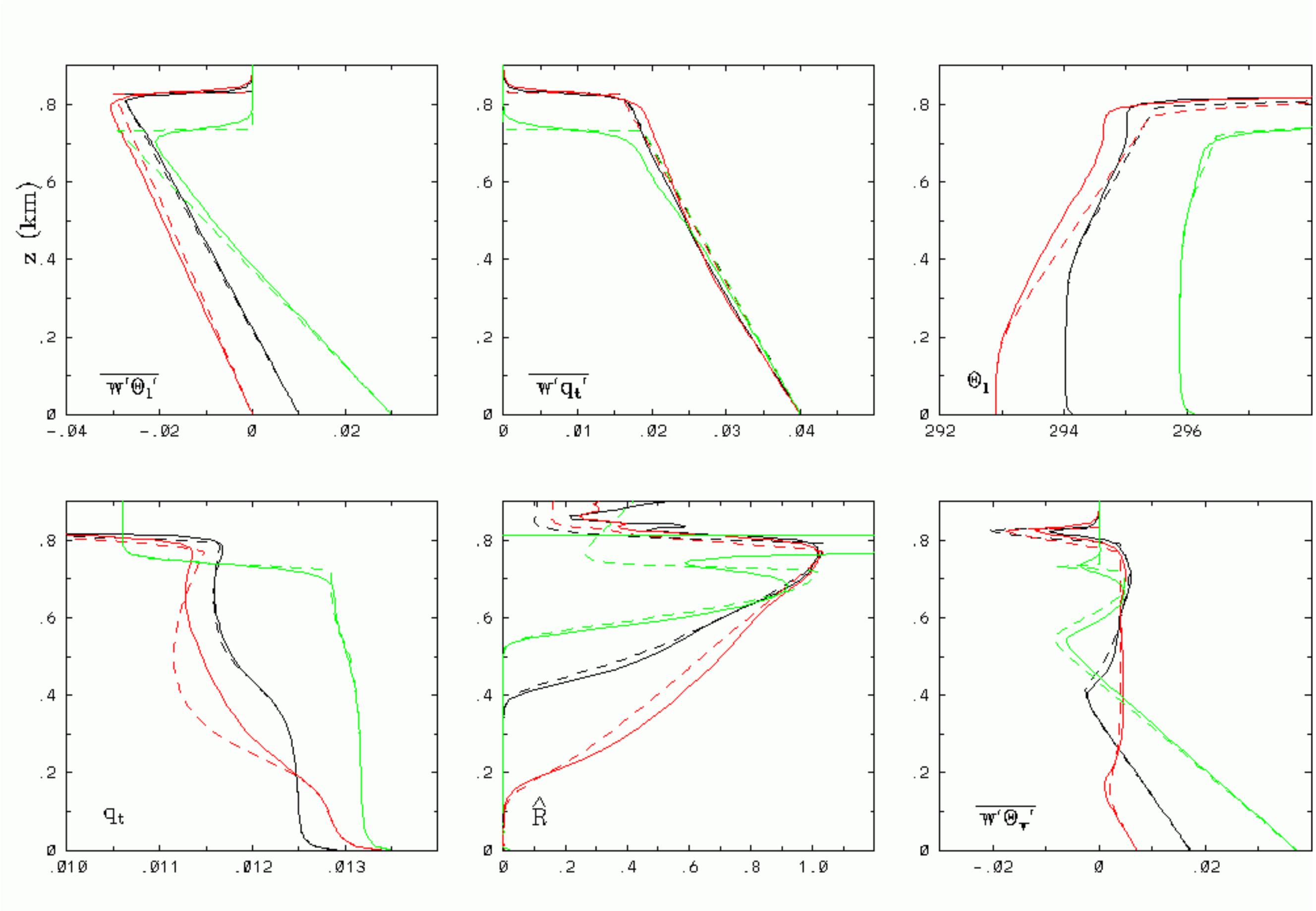

Figure 1. Mean vertical profiles from three sample large eddy simulations of quasi-steady cumulus-coupled boundary layers (red, black, and green lines) showing: liquid water potential temperature flux, total water flux, liquid water potential temperature, total water, R described in the text, and buoyancy flux. The solid lines represent a horizontal time average of the LES data and the dashed lines the predictions discussed in the text following from the entrainment constraints and given values for a limited set of physical inputs. The predictions provide a good representation of the LES data for all profiles.

Results from a previous GCSS intercomparison (Duynkerke et al. 2003) demonstrated that LES does a good job reproducing the basic features of the observed diurnal cycle of marine stratocumulus, including the variations in liquid water path and solar-induced decoupling of the layer in the afternoon. Single column models simulating the same case showed significant variations and compared less favorably with the observations, in large part because of problems correctly predicting the cloud-top entrainment rate.

IMPACT/APPLICATION

A valid model of the marine atmospheric boundary layer is needed not only because its dynamics are critical in transporting the surface fluxes of heat and moisture responsible for driving most atmospheric dynamics, but also because it determines the immediate environment within which many Navy operations are performed. Boundary-layer clouds directly influence both the local environment (e.g.,

for visual, radar, and laser communication) and the global environment (through their impact on the radiation balance). Accurate representation of the buoyancy flux, entrainment rate, and cloud/circulation structure are critical ingredients in correctly modeling the behavior of cloudy boundary layers. We expect this effort to lead to improved subgrid parameterization of these processes in models such as the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) regional model developed at the Naval Research Laboratory (Hodur, 1997).

TRANSITIONS

Stevens et al. 2003 found the entrainment parameterization based on Lewellen and Lewellen 1998 to be one of the few parameterizations they tested that was consistent with their entrainment measurements taken during DYCOMS-II.

Intercomparison results from the GCSS boundary layer cloud modeling working group (http://www.atmos.washington.edu/~breth/GCSS/GCSS.html) have become a standard test set for development and evaluation of parameterizations used in numerical weather prediction and climate models.

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft wakes/contrails for NASA (e.g., Lewellen and Lewellen, 2001), and to model the turbulent interaction of a tornado with the surface for NSF (e.g., Xia et al. 2003). The use of essentially the same LES code on these separately supported efforts works to the advantage of all three projects, particularly in fostering numerical improvements in the efficiency and accuracy of the code.

REFERENCES

Bechtold, P. and A. P. Siebesma 1998: Organization and Representation of Boundary Layer Clouds. *J. of the Atmospheric Sciences,* Vol. 55, 888-895.

Brown, A. R. 1999: The Sensitivity of Large-eddy Simulations of Shallow Cumulus Convection to Resolution and Subgrid Model. *Quarterly J. of the Royal Met. Soc.,* Vol. 125, 469-482.

Duynkerke, P., S. de Roode, M. van Zanten, J. Calvo, J. Cuxart, S. Cheinet, A. Chlond, H. Grenier, P. Jonker, M. Kohler, G. Lenderink, D. Lewellen, C-L. Lappen, A. Lock, C-H. Moeng, F. Muller, D. Olmeda, J-M. Piriou, E. Sanchez, and I. Sednov, 2003: Observations and numerical simulations of the diurnal cycle of the EUROCS stratocumulus case. Submitted to *Quarterly J. of the Royal Met. Soc.*

Hodur, Richard M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Monthly Weather Review,* Vol. 125, 1414-1430.

Lewellen, D.C., and W. S. Lewellen, 1998: Large-Eddy Boundary Layer Entrainment. *J. of the Atmospheric Sciences,* Vol. 55, 2645-2665.

Lewellen, D.C., and W. S. Lewellen, 2001: The Effects of Aircraft Wake Dynamics on measured and simulated NOx and HOx Wake Chemistry. *Journal of Geophysical Research,* Vol. 106, 27661-27672.

Lewellen, D. C., and W. S. Lewellen, 2002: Entrainment and Decoupling Relations for Cloudy Boundary layers. *J. of the Atmospheric Sciences,* Vol. 59, 2966-2986.

Lewellen, D. C., and W. S. Lewellen, 2003: Buoyancy Flux Modeling for Cloudy Boundary layers. Submitted to *J. of the Atmospheric Sciences.*

J. Xia, W.S. Lewellen, and D.C. Lewellen, 2003: Influence of Mach Number on Tornado Corner Flow Dynamics. *J. of the Atmospheric Sciences,* in press.

Stevens, B., D. Lenschow, I. Faloona, C-H. Moeng, D. Lilly, B. Blomquist, G. Vali, A. Bandy, T. Campos, H. Gerber, S. Haimov, B. Morley and D.Thorton 2003: On Entrainment Rates in Nocturnal Marine Stratocumulus. *Quarterly J. of the Royal Met. Soc.,*in press.

PUBLICATIONS

Duynkerke, P., S. de Roode, M. van Zanten, J. Calvo, J. Cuxart, S. Cheinet, A. Chlond, H. Grenier, P. Jonker, M. Kohler, G. Lenderink, D. Lewellen, C-L. Lappen, A. Lock, C-H. Moeng, F. Muller, D. Olmeda, J-M. Piriou, E. Sanchez, and I. Sednov, 2003: Observations and numerical simulations of the diurnal cycle of the EUROCS stratocumulus case. *Quarterly J. of the Royal Met. Soc.*

Lewellen, D. C., and W. S. Lewellen, 2003: Buoyancy Flux Modeling for Cloudy Boundary layers. *J. of the Atmospheric Sciences.*

Siebesma, A. P., C. S. Bretherton, A. R. Brown, A. Chlond, J. Cuxart, P. G. Duynkerke, H. Jiang, M. Khairoutdinov, D. C. Lewellen, C-H. Moeng, B. Stevens and D. E. Stevens, 2003: A Large-eddy Simulation Intercomparison Study of Shallow Cumulus Convection, *J. of the Atmospheric Sciences,* Vol. 60, 1201-1219. [published, refereed]